TITLE

Effect of sand on landing knee valgus during single leg land and drop jump tasks: Possible implications for ACL injury prevention and rehabilitation.

ABSTRACT

Context: Despite significant emphasis on Anterior Cruciate Ligament (ACL) injury prevention, injury rates continue to rise and re-injury is common. Interventions to reduce injury have included resistance, balance and jump training elements. The use of sand-based jump training has been postulated as an effective treatment. However, evidence on landing mechanics is limited.

Objective: To determine potential differences in landing strategies and subsequent landing knee valgus when performing single leg landing (SLL) and drop jump (DJ) tasks onto sand and land, and compare between both male and female populations.

Design: A randomised repeated measures crossover design.

Setting: University Laboratory.

Participants: 31 participants (20 males, 11 females) from a university population.

Interventions: All participants completed DJ and SLL tasks on both sand and land surfaces.

Main Outcome Measures: 2-dimensional Frontal Plane Projection Angle (FPPA) of knee valgus was measured in both the DJ and SLL tasks (right and left) for both sand and land conditions.

Results: FPPA was lower (moderate to large effect) for SLL in sand compared to land in both legs (Left: 4.3º ±2.8º; Right: 4.1º ±3.8º) for females. However, effects were unclear (Left: -0.7º ±2.2º) and trivial for males (Right: -1.1º ±1.9º). FPPA differences for males and females performing DJ were unclear, thus more data is required. Differences in FPPA (land vs sand) with respect to grouping (sex) for both SLL (Left: 4.9º ±3.0º) and (Right: 5.1º ±4.0º) were both very likely higher small/ possibly moderate for females compared to males.

Conclusions: The effects of sand on FPPA during DJ tasks in males and females are unclear, further data is required. However, the moderate to large reductions in FPPA in females during SLL tasks suggests sand may provide a safer alternative to firm ground for female athletes in ACL injury prevention and rehabilitation programs which involve a SLL component.

Key Words: landing knee valgus, sand, ACL**.**

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are common across a number of sports, with a high prevalence in basketball, volleyball and soccer.[1] Most injuries occur during a unilateral jumping or landing task.[2] Despite significant emphasis being placed on injury prevention, injury rates continue to rise [3] and re-injury is common,[4] with significant time lost from sport. Long term prognosis is poor, with increased risk of tibiofemoral and patellofemoral osteoarthritis.[5] Risk of ACL injury would also appear gender specific, with females demonstrating at least three times greater risk than their male counterparts.[6] The increased risk in females is likely multi-faceted, and may include anatomical differences and hormonal changes,[7] although an increased knee valgus position on landing is frequently cited.[8,9] Establishing an effective intervention to help reduce injury occurrence and accelerate the rehabilitation process would be desirable in both populations.

Increased knee valgus on landing is a biomechanical risk factor for non-impact ACL injury among athletes.[9] Specifically, increased knee valgus during drop jump tasks on firm ground has been prospectively associated with ACL injury in female athletes.[9] Individuals with increased landing knee valgus have also shown the same movement patterns in cutting and pivoting tasks, which may further increase their ACL injury risk.[10] A number of previous studies have investigated landing knee valgus using 3D analysis.[8,9,11] However, the limited availability of 3D analysis in clinical practice due financial, spatial and temporal costs has led to the preferred use of 2D techniques that employ less expensive, portable and easy to use equipment.[12] 2D analysis using the frontal plane projection angle (FPPA) has been shown to be a valid and reliable method to quantify knee valgus motion during a number of jumping tasks.[13] The FPPA has also been shown to relate to 3D measures of joint kinematics.[9]

Individuals with large landing valgus angles should therefore be suspected of demonstrating 3D kinematics thought to be detrimental to the ACL during functional activities.[14]

Interventions which can reduce landing valgus angles in athletes should be integral to injury prevention and rehabilitation programs for ACL injuries. Jump training programs in isolation have been shown to be as effective at reducing landing knee valgus, and potential ACL injury risk, as those with additional balance and strength training components.[15] Herrington[15] and Kato et al[16] both demonstrated that a 4 week jump training program led to a significant decrease in knee valgus during a jump shot landing, with values ranging from 36-41%. To date, jump training programs, such as these, have been conducted on firm surfaces[17] which exacerbate musculoskeletal loading. However, the efficacy and utility of softer surfaces such as sand in training interventions has been suggested.[18] Previous studies have demonstrated a reduced rate, and extent of musculoskeletal loading in jumping activities on sand[19,20] with a nearly fourfold reduction in impact forces on soft dry sand compared to firm wet sand[21] and grass surfaces.[22] Modified muscle activation strategies that provide more joint stability[23] when training on sand compared with firm surfaces have also been highlighted. Furthermore, evidence of improvements transferring to future firm ground performance in jumping as well as running, agility, and strength tasks has been well documented.[24-27] Recent work using 3D motion capture demonstrated that the knee abduction moment (KAM), a significant predictor of knee valgus[9,12] and subsequent ACL injury risk was reduced on a sand compared to a firm surface during a single leg jump task.[28] However, the magnitude of the effect of sand on landing knee valgus specifically is unknown. If jump training on sand can reduce musculoskeletal loading in addition to a reduction in ACL injury risk, this could have significant implications for the safety of both ACL rehabilitation and injury prevention interventions, specifically for individuals considered to be at a heightened injury risk.

To date, no study to our knowledge has examined the effects on landing knee valgus using a sand compared with a firm surface during jumping tasks. The aim of our study was to determine whether differences were apparent in landing strategies and subsequent landing knee valgus (FPPA) during a bilateral drop jump (DJ) and single leg landing (SLL) task onto both sand and firm surfaces, and compare between both male and female populations. The DJ and SLL task were chosen as they simulate landings encountered during sporting activity.[14]

METHODS

Participants

Thirty-six participants (16 female 20 male) who participated in a minimum of three hours of sporting activity per week and were involved in jump related sports (basketball, soccer, volleyball, rugby) were recruited from a university population. Sample size was based upon a previously published study demonstrating a clear effect for the outcome[15] and a reliability study.[29] Five females were excluded, two for previous ACL injury and three for a lower limb injury within the last six months. Subsequently, thirty-one participants (11 females, age: 23.7 ± 0.8 years; body mass: 69.2 ± 12.2 kg; height: 162.3 ± 8.0 cm and 20 males, age: 25 ± 10.8 years; body mass: 76.6 ± 4.1 kg; height 178.3 ± 4.9cm) undertook testing on one occasion. All participants had no history of ACL injury or other knee pathology, previous significant lower limb fracture or surgery and had been injury free for six months prior to data collection. All participants provided written informed consent, with the study approved by the University's ethics committee, in accordance with the Declaration of Helsinki.

Procedures

A randomised repeated measures crossover design was implemented adapting a previously employed protocol.[14] Prior to testing, a standardised sub-maximal warm-up was performed which included 10 min on a stationary bike, stretching of the gluteus maximus, hamstrings, quadriceps and gastrocnemius. Participants were fitted with a heart rate monitor and asked to cycle at 60 % of their age predicted maximum heart rate. All muscle groups were stretched statically (3 x 30 s duration), with participants instructed to stretch to the 'point just before pain'.[28] The total stretch duration was kept lower than 2 minutes for each muscle group as this is the suggested 'cut off' period for time under tension of a muscle before a stretch induced impairment in muscle performance is observed.[30.]

Subsequently, participants performed a bilateral DJ, and SLL task (right and left leg) on both firm ground and a sand surface. Participants performed three familiarisation trials of each jump on both surfaces to reduce confounding from habitation. The test-retest reliability of these jumps has been previously established as good to excellent ICC (r = 0.89-0.92).[31] Participants then performed three trials for each jump task on each surface (land and sand) with a standardised rest phase between jumps. Jump tasks were performed in a randomised order using a computer-generated system, with the surface type counterbalanced in a repeated measures crossover design. All participants refrained from caffeine at least 24 h prior, and strenuous muscular exercise for ~48 h prior to testing.

For the DJ task participants were instructed to stand on a 30 cm box (Foam Plyometric Box, Perform Better Ltd., UK) and drop directly down onto a predetermined floor marker 30 cm from the box (Fig. 1 and 2) landing on both feet and immediately performing a maximum vertical jump, raising both arms to provide countermovement.[14] For the SLL task participants were instructed to step off a 30 cm box landing with the opposite leg onto a predetermined floor marker 30 cm from the box holding the position.[14] The sand (particle size 0.02-0.2 mm) (Building Sand, Wickes, UK) was placed in a purpose-built pit at a depth of 10 cm and placed directly in front of the box (Fig. 1 and 2). When performing the DJ or SLL task onto sand participants were again instructed to land on a predetermined marker 30 cm from the box. For the sand conditions a 40 cm box was used to account for the change in height (Fig. 1). Following each landing on the sand surface the sand was raked prior to the next jump to ensure an evenly distributed surface and a consistent 10 cm depth. All participants wore standardised plimsoll shoes during all jumping tasks to minimise any adverse footwear effects on the landing position.

Throughout testing participants were required to wear retro reflective markers positioned over dark tight fitted clothing to allow for visualisation of markers. Markers were placed on the anterior superior iliac spine (ASIS), mid tibiofemoral joint (TFJ) and mid ankle mortise bilaterally[14] (Fig. 1). Midpoints were determined using a standard tape measure. 2D frontal plane projection angle (FPPA) of knee valgus alignment was measured during the two tasks on each surface.[14] A high-speed digital video camera (Quintic GigE 1mp, Quintic Consultancy Ltd, West Midlands, UK) recording at 100 frames per second was positioned 2 m anterior to the subjects landing target at the height of the participant's knee (Fig. 2), and aligned perpendicular to the frontal plane.[14] Images captured were imported into a digitising software program (Quintic 29, Quintic Consultancy Ltd, UK) ready for analysis. The valgus angle of the knee was recorded as that formed between the line from the ASIS and mid TFJ markers and the line from the mid TFJ and mid ankle mortise markers[14] (Fig. 1). The angle was captured using the frame which corresponded to the lowest point of the landing phase. Positive and Negative FPPA values reflected knee valgus and varus respectively. The average FPPA value from three trials during each task on each surface was used for analysis. One investigator digitized all the data from all participants. Thirty randomly selected knee valgus angle videos (including males and females across both jumping tasks and both surfaces) were re-assessed to establish the intra-rater reliability.

Figure 1. Frontal plane projection angle (FPPA) during (a and b) Drop jump, and (c and d) Single leg landing tasks on land and sand surfaces.

Insert Fig. 1 here

Figure 2. An illustration of the experimental set up.

Insert Fig. 2 here

<u>Statistical analyses</u>

All raw data were deemed to be acceptably normally distributed following visual assessment of Q–Q plots and histograms, and are subsequently presented as mean ± standard deviation (SD). For intra-rater reliability, data were first log transformed to reduce non-uniformity of error, and subsequently back transformed and expressed as a percentage.[32] The intra-class correlation coefficient (ICC 3,1; Shrout and Fleiss [33]) was calculated using a two- way mixed effects model (SPSS v.25, Armonk, NY: IBM Corp). Typical error of the measurement was calculated using previously cited equations [34]. To assess the magnitude of the typical error the between-athlete pooled SD was multiplied by half the standardised thresholds <0.1, 1.0 and 3.0 (trivial, small and moderate). The trivial, small and moderate thresholds for the typical error were 10.0%, 11.1% and 33.4%. Qualitative inference of the ICC (3,1) was based on established previous thresholds.[35]

As the sample population is made up of ~50% more males than females, the peak landing knee valgus angle for male and female groups were initially analysed separately. Subsequently, a Paired Samples *t* test was used for DJ left, and right and SLL left and right for the subgroups. The mean difference, degrees of freedom, and P value from each test were used to derive magnitude based decisions (MBD).[32] To assess the combined group effects, the outcome effects, and error degrees of freedom from both groups were combined using a custom designed spreadsheet.[32] Differences in the outcome between groups (A-B) represent the effect of the grouping variable on the outcome. The mean (A-B/n) of the outcomes across the groups represents the outcome adjusted appropriately for the effects of the grouping variable (male, female), allowing for unequal variances due to the unequal sample sizes.[34]

Uncertainty in all outcome measures was expressed with 90% compatibility intervals (CI). Reference Bayesian analysis with a dispersed uniform prior was used to make inference on the true magnitude and uncertainty of effects. In the absence of a minimum clinically important difference, standardised thresholds of 0.2, 0.6, and 1.2 were multiplied by the between athlete SD (pooled from both conditions and adjusted for small sample bias) to anchor small, moderate and large effects respectively.[34] Subsequently, the chance of change being substantial or trivial was calculated by converting the *t* statistic for the effect with respect to the threshold (change – threshold / standard error of the change) to a continuous probability via a one-sided *t* -distribution.[32] The likelihood of the true effect being the observed magnitude was indicated by the following scale; possibly (25 to < 75%), likely (75 to < 95%), very likely (95 to < 99.5%) and most likely (≥ 99.5%).[32] All effects were evaluated non-clinically, whereby a difference was deemed unclear if its chance of being both substantially positive and negative was ≥ 5%

(based on the threshold for a small effect). A Bonferroni adjustment was applied to account for multiple comparisons and reduce risk of type I error. Therefore 98% CI were used when deriving the MBD. However, the 90% compatibility limits (CL) are reported. Finally, the second generation p-value (pδ) is reported for all outcomes. The pδ represents the proportion of data-supported hypotheses that are also null hypotheses. As such, pδ indicate when the data are compatible with null hypotheses (pδ = 1), or with alternative hypotheses (pδ = 0), or when the data are inconclusive (0 < pδ < 1).[36]

RESULTS

The ICC (3,1) for the intra-rater reliability was very high[35] (0.98; 90% CI = 0.95 to 0.99), the magnitude of the typical error was trivial (6.8% ± 5.9%). Means and standard deviations for FPPA values during SLL and DJ tasks for both males and females across both land and sand conditions are displayed in Table 1. The mean difference ±90% CL for all jumps across conditions for male and female subgroups are displayed in Table 2. Compared with landing on a firm surface during a SLL task, FPPA was lower for Right (likely small/possibly moderate), and Left (very likely moderate/possibly large) sides when landing on a sand surface in females. Effects in males were unclear (Left), and possibly trivial/possibly small increase (Right), therefore effects are not definitively substantial. Differences in landing FPPA observed in the DJ between surfaces in females and males were unclear with CL spanning both substantially positive, and substantially negative.

The combined effects of male and female subgroups for each jump between the two conditions are displayed in Table 3. When combined, DJ landing effects (left) remained unclear with a likely trivial combined effect for DJ Right, and a possibly small/ possibly trivial effect of the grouping variable. When male and female were combined, the certainty in the effects, and magnitude of the effects for SLL (left & right) reduced demonstrating possibly small/possibly trivial reductions in FPPA for sand. The differences in the outcome (FPPA land vs. sand) with respect to grouping (sex) for both SLL left (4.9º ± 3.0º) and right (5.1º ± 4.0º) were both very likely higher (small)/ possibly moderate for females compared to males.

Table 1. Frontal plane projection angles (mean ± SD) for females and males (left, right and combined) for single leg landing and drop jump tasks across both land and sand conditions.

	Females						Males					
	SLL			DJ			SLL			DJ		
	L	R	C	L	R	C	L	R	C	L	R	C
LAND												
M±SD	11.9±3.5	11.2±4.8	11.6±4.1	10.0±5.0	7.8±4.9	8.9±5.0	1.5±6.9	1.9±7.5	1.7±7.1	-2.7±7.1	-1.0±10.0	-1.9±8.6
SAND												
M±SD	7.7±2.5	7.2±5.6	7.4±4.2	10.2±4.5	7.2±5.5	8.7±5.1	2.1±5.3	3.0±7.4	2.5±6.4	-1.5±6.8	0.6±9.7	-0.4±8.4

Abbreviations: SLL: Single Leg Landing, DJ: Drop Jump, M: Mean, SD: Standard Deviation, L: Left, R: Right, C: Combined

Table 2. Mean difference (MD) ±90% compatibility limits (CL) with magnitude based decisions, and the second generation p-value (Pδ) for all jumps across conditions for male (n =20) and female (n = 11) subgroups.

	MD (degs) (90% CL) (Land-Sand)	Qualitative interpretation	Threshold for small (degs)	Pδ
<u>Females</u>				
DJ-L	-0.12 ±3.0	Unclear	1.1	0.5
DJ-R	0.64 ±2.8	Unclear	0.9	0.5
SLL-L	4.3 ±2.8	*** moderate/ * large ↓	0.6	0
SLL-R	4.1 ±3.8	** small/ * moderate ↓	1.0	0
<u>Males</u>				
DJ-L	-1.3 ±3.2	Unclear	1.4	0.5
DJ-R	-1.6 ±3.0	*trivial/*small ↑	2.0	0.5
SLL-L	-0.7 ±2.2	Unclear	1.2	0.5
SLL-R	-1.1 ±1.9	* trivial/* small ↑	1.5	0.5

Note: * = possibly, ** = likely, *** = very likely for the qualitative inference. The arrow denotes either an increase ↑ or decrease ↓ in knee valgus on the sand surface, **DJ-L** = drop jump landing left, **DJ-R** = drop jump landing right, **SLL-L** = single leg landing left, **SLL-R** = single leg landing right, pδ = second generation p=value

Table 3. Combined effects of male and female subgroups for each jump between conditions.

Jump Task	Mean difference (90% CL) for combined group effects	Qualitative interpretation	Threshold for small
DJ-L	[a]1.2 ±4.3	Unclear	1.7
	[b]-0.7 ±2.1	Unclear	
DJ-R	[a]2.2 ±4.0	*small/*trivial ↑ for females	1.9
	[b]-0.5 ±2.0	**trivial ↓ for land	
SLL-L	[a]4.9 ±3.0	*** small / ** moderate ↑ for females	1.3
	[b]1.8 ±1.5	* small/ * trivial ↑ for land	
SLL-R	[a]5.1 ±4.0	*** small/ * moderate ↑ for females	1.5
	[b]1.5 ±2.0	* small/*trivial ↑ for land	

Note: a = female – male effects, b = female – male / 2 effects; * = possibly, ** = likely, *** = very likely for the qualitative inference, **DJ-L** = drop jump landing left, **DJ-R** = drop jump landing right, **SLL-L** = single leg landing left, **SLL-R** = single leg landing right.

DISCUSSION

The aim of our study was to determine whether differences were apparent in landing knee valgus (FPPA) during a bilateral DJ and SLL task onto both sand and firm surfaces, and to compare between both male and female populations. Landing knee valgus has been established as a significant risk factor for ACL injury,[9] and females are known to have a much greater ACL injury risk than their male counterparts.[6] The primary finding of this study was FPPA was lower (ranging from likely small/possibly moderate (right leg) to very likely moderate/possibly large (left leg) in magnitude) during a SLL task onto sand compared to a firm surface in females only. Differences in effects were unclear for males with the uncertainty in the effects spanning both substantially negative and substantially positive; more data are required before a clear outcome can be inferred in this population. The magnitude of the reduction in FPPA for SLL on sand compared to land for females provides some initial support for the use of a sand surface with this group to reduce landing knee valgus and potentially ACL loading during jumping tasks, which involve a SLL component. Further research would still need to be conducted to build upon these preliminary findings, and to establish whether a period of jump training on sand provides the stimulus needed for improvement in landing knee valgus during future firm ground performance.

To the authors knowledge this is the first study to quantify the magnitude of differences in landing knee valgus (FPPA) between different jump landing tasks on sand compared to a firm surface. As such there is limited evidence with which to compare. Whilst effects were unclear for DJ landing protocols, unilateral landings are a more common ACL injury mechanism than bilateral landings across female sports.[2] Furthermore, strong correlations (R = 0.63-0.86) have been reported between knee valgus angles on SLL, cutting and pivoting tasks[10] which may suggest that the results of the SLL task are more meaningful with regard to potential reduction in ACL injury risk.

Although, increased landing knee valgus has been cited as a significant predictor of ACL injury in female athletes,[9] the amount of landing knee valgus which becomes clinically meaningful in terms of increasing injury risk to the ACL remains unclear. Herrington & Munro[14] attempted to establish normative values with respect to knee valgus, and individuals outside of these values are suggested to be at a higher risk, and possibly warrant inclusion in appropriate preventative exercise programmes. For unilateral step landing tasks using a 2D FPPA method, normative landing knee valgus values of 5-12º for females were suggested, using an active university population. However, further studies are required to establish if the normative values show true sensitivity in detecting at risk populations.

Our study, demonstrated a similar range of landing knee valgus values for recreationally active females (5.1º-19.1º) during the SLL task on a firm surface. The mean landing knee valgus of (11.6º ± 4.1º) on land during SLL is close to the suggested upper limit of 'normal', which could indicate that the female participants were a higher risk group. A mean value of (1.7º ± 7.1º) in the male group during the SLL task on land, is also within previously reported normative values of 1-9º for males.[14] These findings may explain in part why males have a roughly three times lower ACL injury risk than their female counterparts.[6] Moreover, males have been reported to be more prone to ACL injuries in the sagittal plane, with females being specifically vulnerable to frontal plane instability and subsequent valgus collapse.[37]

Mean FPPA reduced by (4.3º ± 2.8º, left) and (4.1º ± 3.8º, right) (Table 2) in females during the SLL task on sand. This mean reduction of ~ 4º may have brought the females into a 'safer' landing knee valgus range as per the reported values of Herrington and Munro[14]. A decrease of 4.4º in landing knee valgus has been shown to correspond to a 19% decrease in KAM previously,[38] with increased KAM being a significant predictor of ACL injury risk.[9] The ~ 4º decrease observed in our study is consistent with previous 3D analysis[28] where a 15% reduction in KAM was noted when landing onto a sand surface compared to a firm one during a single leg jump task. The study analysed the pooled effects of both males and females, rather than assessing these groups separately as our study has performed. However, the sample was predominantly female (14 females and 3 males). When combined effects of males and females were analysed in our study differences in the magnitude of effects of surface reduced and were less certain (possibly small/ possibly trivial: Table 3). The reduced combined effect observed in our study could be due to the different motion capture techniques (3D vs. 2D).

Higher mean FPPA values were noted during SLL compared to DJ tasks for both females (11.6º ± 4.1º vs 8.9º ± 4.9º) and males (1.7º ± 7.1º vs -1.85º ± 8.6º), which is consistent with the findings of others.[39,40] Although ground reaction force (GRF) was not reported in our study, previous authors[40] have noted similar GRF characteristics during both SLL and DJ tasks. This effectively means that forces experienced by the limbs are doubled during a unilateral task with a subsequent increased demand to decelerate the landing force.[39] Reductions in landing knee valgus in females during SLL may be due to the attenuation of the vertical GRF found with sand vs. harder surfaces.[21] This would be less apparent in a DJ, with the GRFs more evenly distributed between legs, and may account for the lack of effect observed between surfaces in this task. However, this does not explain the trivial and unclear effects observed in males during SLL. Females however, often display neuromuscular imbalances such as ligament and trunk dominance during landing that are not seen in their male counterparts and may put them at greater ACL injury risk.[41] ‘Ligament dominance’ in females may allow the motion of the knee on landing to be directed more by GRFs than their own musculature, while 'Trunk dominance' may contribute to the often excessive trunk motion observed in females in the frontal plane on landing.[41] Both of these landing strategies would lead to higher GRFs being experienced by the athlete. The diminished GRFs when landing onto the sand surface may have helped alter these landing strategies in the female participants, which may account for the gender differences noted in landing knee valgus during the SLL task.

It could be argued that the diminished GRFs on sand might limit the training specificity needed for firm ground performance. Howatson and Van Someren[42] suggest that exercise-induced muscle damage (EIMD) and the inflammatory process to exercise may be an important stimulus for the muscular repair and adaptation process. Therefore, jump training on a lower impact surface could hinder muscular adaptations. However, previous research has demonstrated improvements in firm ground performance following a training stimulus on sand in a number of tasks (jumping, running, agility, strength) [24-27], with adaptations such as enhanced motor unit recruitment and increased activation of synergists amongst the proposed mechanisms cited.[27] Furthermore, Pinnington et al [23] noted that running on sand led to an increased recruitment of the hamstrings, Vastii, Rectus femoris and Tensor Fascia Latae on a sand compared to a firm surface during the stance phase. An increased activation of the hamstrings specifically at initial foot contact and mid stance at both 8 and 11-km.h^{-1} was noted on the sand surface. As the unstable nature of a sand surface may increase stance time fourfold (14ms versus 49ms) [21] compared to a firm surface, a relatively greater active muscle mass may be required during the stance phase and could explain the findings observed here. The role of muscle control during landing such as the co-contraction of the quadriceps and hamstring muscles, as well as elevated gastrocnemius activity in reducing ACL injury risk has been well established.[43,44] Females specifically have been shown to have reduced hamstring activation when landing compared their males counterparts, with a more ‘quadriceps dominant’ strategy adopted, [9] which may contribute to their increased ACL injury risk. If a similar increase in hamstrings and quadriceps co-activation occurred for females during the SLL task on sand, to that noted in running tasks on sand [23], this may account for the gender differences observed between the surfaces during this task. It would also suggest that repeated exposure to sand may lead to muscle activation strategies in females that promote stability and subsequently reduce ACL injury risk. Further investigation however, into muscle activation strategies when jumping onto a sand compared to a firm surface would be beneficial to help confirm this conjecture. This would help establish whether muscles that are known to be important in reducing ACL injury during jumping tasks demonstrate greater activation on sand compared with a firm surface. It would also highlight whether any gender specific differences in muscle activation during jumping tasks on different surfaces occur.

Expectations of surface stiffness change may also account for the changes in landing knee valgus we observed here when comparing sand to a firm surface. Changes in landing kinematics and muscle activation prior to landing has been demonstrated previously, when athletes are expecting a surface stiffness change.[45] An almost 50% decrease in leg stiffness was observed when participants were expecting to land on a firm compared to a softer surface. Participants landed with more knee flexion and increased their muscle activation by up to 76% during the 50ms prior to landing on an expected hard compared to a soft surface. Although electromyography (EMG) was not performed in our study it is likely that some neural anticipation would have occurred, as participants were not blinded to the landing surfaces and may well have adapted their landing strategy for the expected surface stiffness change when landing on a sand compared with a firm surface.[45]

Despite our findings, it is important to highlight potential limitations. Although we considered the unequal sample sizes between males and females in our statistical design, the smaller sample size in the female population should be given due consideration when interpreting the results. However, clear beneficial effects were still observed in this group. The use of 2D FPPA is less sensitive to subtle joint movements such as knee valgus, and possible movement artefact with skin markers can also occur[46] affecting the accuracy of measurement. However, 2D FPPA has previously been shown to be both a valid and reliable measure of lower extremity dynamic knee valgus, with evidence of a correlation to 3D analysis, although this still needs to be firmly established.[39] The magnitude of the differences observed between the surfaces in female participants in the SLL task (~ 4º) is also higher than the standard error of measurement previously reported using this method, suggesting these differences are a true reflection of the effects of the conditions rather than measurement noise. Furthermore, the 36% (11.6º down to 7.4º) reduction for females in mean landing knee valgus during the SLL task on sand is similar in magnitude to the reduction noted in landing knee valgus (36-41%) during a jump shot following 4 weeks of jump training[15-16]. Finally, although we ensured a consistent depth of 10 cm when landing on the sand surface, characteristics such as granulation and moisture content as well as depth of sand can affect its stiffness.[23] Future studies should therefore look to quantify the peak impact deceleration force of compared surfaces, and the effects of different sand conditions on landing knee valgus.

CONCLUSIONS

Our study confirms previous reports of reduced knee loading on landing in sand compared to firm surfaces using 3D motion analysis. We provide further evidence that 2D FPPA (landing knee valgus) is reduced in sand compared to land during SLL. However, definitive and substantial reductions were noted in females only, who remain at the greatest injury risk. The finding provides further support for the potential use of sand as a safer alternative to firm ground in ACL injury prevention and rehabilitation programs, which involve a single leg jumping component. Those clinicians involved in ACL injury prevention and rehabilitation programs, may wish to consider the use of sand with females when planning jump training that involves a SLL component. The reduced landing knee valgus in sand may have the potential to reduce ACL injury risk in females specifically, and could also enable an accelerated rehabilitation program, as jump training could potentially be implemented more safely at an earlier stage in the process before transitioning to firm surfaces in readiness for a return to sport. Future research should look to establish whether jump training on sand provides the stimulus needed for improvement in landing knee valgus during firm ground performance.

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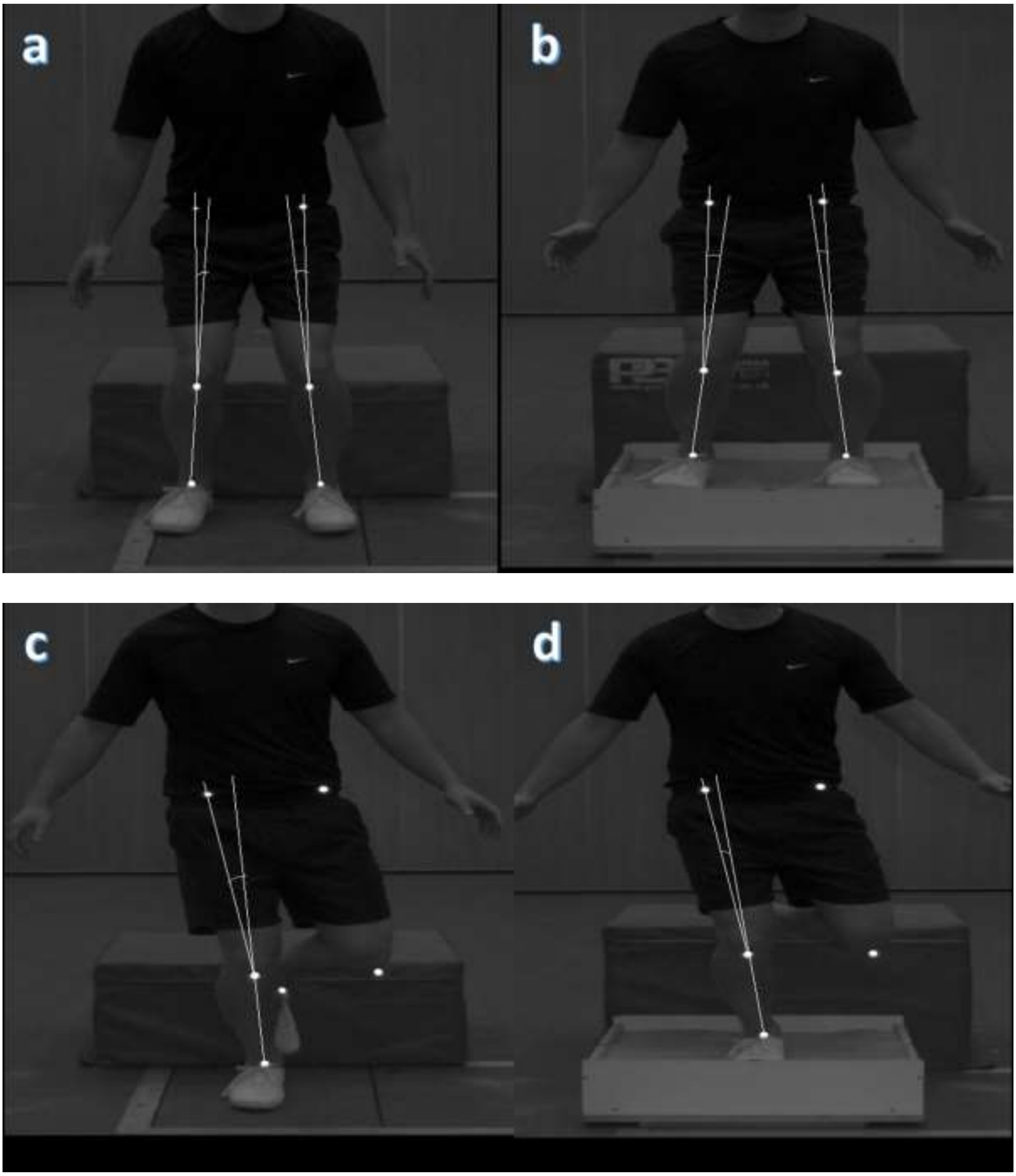
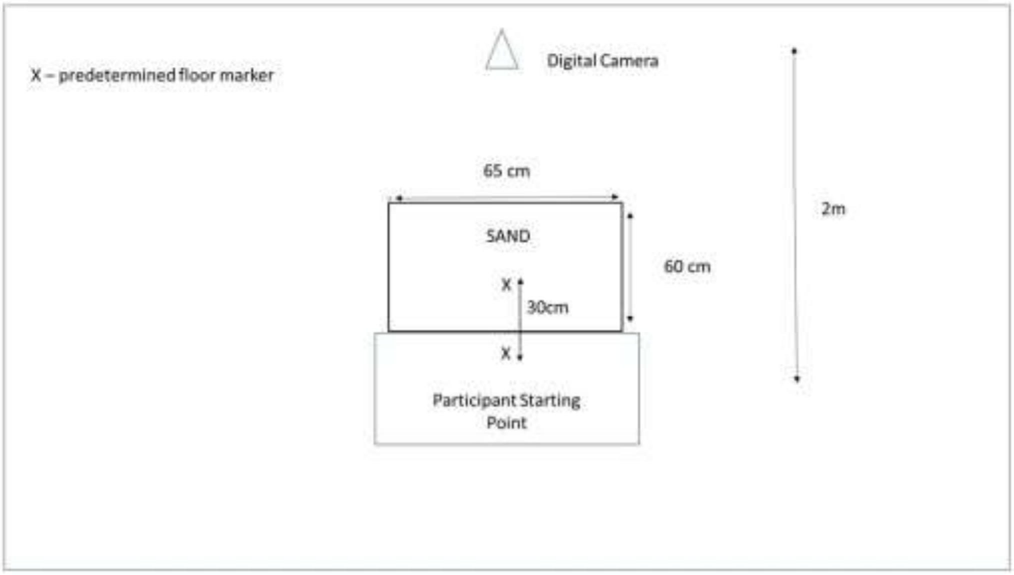
Figure 1



671 Figure 2



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